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IN THE UNITED STATES PATENT AND TRADEMARK OFFICE
APPLICATION FOR UNITED STATES LETTERS PATENT

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TITLE:	TRANSMISSIBILITY SHAPING CONTROL FOR ACTIVE VEHICLE SUSPENSION SYSTEMS
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BACKGROUND

1. Field of the Invention

[0001] The present invention generally relates to active vehicle suspension systems. More specifically, the invention relates to transmissibility shaping control for active vehicle suspension systems.

2. Description of Related Art

[0002] Generally, people all over the world drive their automobiles to various destinations. In order for these people to enjoy the ride to their destinations the suspensions systems in the automobiles must be stable and as comfortable as possible. Typically, different types of automobiles have various suspension systems, which control the ride and handling performance of the vehicle. For example, some vehicles may have a stiff suspension system that limits movement of its vehicle chassis with respect to the road wheels, but provides less isolation from rough road surfaces. In contrast to the stiff suspension system, some vehicles may have a soft suspension system that provides a more comfortable ride by isolating the vehicle occupied from the rough road surface, but allowing increased vehicle chassis movement causing a decrease in the handling performance.

[0003] These suspension systems also include various components, such as shock absorbers. Shock absorbers receive and take up shock that would normally be exerted on the wheels of the vehicle in order to improve the ride performance and the vibration of the wheels. The vibration of the wheels triggers the suspension system to vibrate in an uncontrollable manner. The suspension system vibrates at different frequencies, which may make the suspension system unstable and arduous to control. By adjusting damping with semiactive dampers, semiactive suspension

system can improve ride performance, but provide limited improvement of vehicle handling.

[0004] Usually the dynamics related to vehicle suspension systems have a frequency range of up to 25Hz, which includes two modes: vehicle body mode around 1Hz and wheel hub mode around 11Hz. Traditionally, the luxury vehicle suspension has soft suspension with the body mode frequency of less than 1Hz, while sports vehicles have very stiff suspension with larger than 1Hz body mode frequency for good handling. Generally passive suspensions are designed with a trade-off of ride comfort and handling.

[0005] Automotive OEMs and suppliers are working on active suspension systems to improve vehicle ride and handling performance. Typically active suspension systems employ hydraulic actuators and use control algorithms requiring force feedback. In addition, these systems may require up to 7.5Kw during operation with a fully hydraulic active suspension system. The amount of power required is a significant disadvantage for implementation.

[0006] In view of the above, it is apparent that there exists a need for improved system and method for controlling active suspensions.

SUMMARY

[0007] In satisfying the above need, as well as overcoming the enumerated drawbacks and other limitations of the related art, the present invention provides a transmissibility shaping control for active suspension systems.

[0008] An embodiment of the present invention, described herein, a compressible fluid struts (CFS) including a digital displacement pump-motor (DDPM)

is provided. The CFS is described as having continuously variable semi-active (CVSA) valves for damping tuning. However, the transmissibility shaping (T-shaping) control of the present invention is also applicable to vehicle suspension systems having a CFS without CVSA valves.

[0009] For an active vehicle suspension, it is possible to break the active forces into two tunable forces: one is the damping force from damping tuning and the other the elastic force related to the spring rate or stiffness. Therefore the suspension performance, which can be identified per the transmissibility shape in the frequency domain, is determined by these two tunable elements: damping and stiffness. The system tunes the damping and stiffness elements in combination with frequency information to improve the suspension performance. Studies have shown that the level of stiffness and damping can have significantly different effects on the suspension transmissibility in different frequency ranges. Therefore, separate control strategies are required for the different frequency ranges to reduce the effect of vibration on the wheel and/or body of the vehicle. In addition, for situations requiring improved handling, a stiff suspension can be provided by maximizing the stiffness and damping coefficients.

[0010] T-shaping control of the present invention uses the suspension travel measurement signals and vehicle body accelerations to improve vehicle ride and handling. Additional vehicle signals including lateral acceleration, steering wheel, gas pedal, brake pedal, and longitudinal velocity may also be utilized to identify the vehicle driving situations in order for controller to properly control the ride control, roll control and pitch (dive/squat) control.

[0011] Further aspects, features and advantages of this invention will become readily apparent to persons skilled in the art after a review of the following description, with reference to the drawings and claims that are appended to and form a part of this specification.

BRIEF DESCRIPTION OF THE DRAWINGS

[0012] FIG. 1 is a diagrammatic view of an active suspension system using compressible fluid struts in accordance with the present invention;

[0013] FIG. 2 is a diagrammatic view of a compressible fluid strut with a digital displacement pump motor in accordance with the present invention;

[0014] FIG. 3 is a plot of the sprung mass transmissibility illustrating the effect of stiffness and damping on vehicle dynamics;

[0015] FIG. 4 is a plot of the tire transmissibility illustrating the effect of stiffness and damping on the vehicle dynamics;

[0016] FIG. 5 is a diagrammatic view of the transmissibility shaping control configured to control a digital displacement pump motor and compressible fluid strut based active suspension system in accordance with the present invention;

[0017] FIG. 6 is a plot of the sprung mass acceleration due to pure tone vibration for an active and passive suspension system;

[0018] FIG. 7 is a plot of the sprung mass accelerations due to discrete events for an active and passive suspension system;

[0019] FIG. 8a is a plot of the lateral acceleration during a constant radius maneuver; and

[0020] FIG. 8b is a plot of the vehicle roll angle for an active and passive suspension system during a constant radius maneuver.

DETAILED DESCRIPTION

[0021] Referring now to the drawings, in Fig. 1 a vehicle 10 is shown having an active suspension system 12 embodying the principles of the present invention. Active suspension system 12 includes an electronic control unit 16, a digital displacement pump-motor 18, compressible fluid struts 14, and sensors 15.

[0022] Electronic control unit 16 of the active suspension system 12 interfaces with sensors 15 and other vehicle subsystems to collect suspension travel, suspension travel velocity, and other relevant vehicle information, such as: steering angle, lateral acceleration, and longitudinal velocity to determine and implement a control strategy to optimize the suspension performance. The electronic control unit 16 utilizes the control strategy to operate DDPM 18 to tune the stiffness and damping characteristics of each compressible fluid strut 14.

[0023] Now referring to Figure 2, while a compressible fluid strut 14 for one corner of the vehicle is shown in further detail it is understood that a strut is provided at each wheel. The electronic control unit 16 is connected to DDPM 18, high pressure valve 26, and the low pressure valve 30. The digital displacement pump motor 18 being in fluid communication with reservoir 32 through HP valve 24 and strut 14 through HP valve 26 can actively charge or discharge fluid from reservoir 32 to tune compressible fluid strut 14. An isolator 24 disposed between HP valve 24 and strut 14, isolates the silicon gel contained in compressible fluid strut 14 from the non-compressible liquid contained in DDPM 18.

[0024] In a default state, high pressure valves 26 are closed and the low pressure valves 30 are open. Thus, for the default state, suspension system 12 is passive while DDPM 18 is idle. To increase the pressure in the compressible fluid

strut 14 the high pressure valve 26 is in the default state while the low pressure valve 30 is actively closed. Conversely, to decrease the pressure, high pressure valve 26 is actively opened while low pressure valve 30 is actively closed.

[0025] With regard to suspension control systems, three basic factors should be considered: ride control, drive/squat control, and handling control. For the drive/squat and handling control, a stiff suspension is preferred. Thus, the preferred control strategy should tune the suspension system to have maximum stiffness and damping level thereby reducing the body roll angle and wheel-hop motions for improved handling.

[0026] The control strategy with respect to ride comfort is far more complex than the squat/drive control and handling control strategy. Per the suspension dynamic characteristics, two factors should be considered: primary and secondary ride. The primary ride concerns the body mode control while the secondary ride concerns the wheel-hop mode control.

[0027] Now referring to Figures 3 and 4, the transmissibility present in a Q-car (Quarter-car) model is shown to illustrate the vehicle ride dynamics. The sprung mass or vehicle transmissibility plot is shown in Figure 3. Line 40 represents the sprung mass transmissibility for normal stiffness and small damping. Line 42 represents the sprung mass transmissibility for normal stiffness and large damping. Similarly, line 44 represents the sprung mass transmissibility for small stiffness and small damping. Different frequency ranges are defined according to the effect of stiffness and damping. There are five ranges: low frequency range, body mode frequency range, medium frequency range, wheel-hop mode frequency range, and high frequency range.

[0028] The unsprung mass or tire transmissibility is illustrated in Figure 4. Line 46 represents the unsprung mass transmissibility for normal stiffness and small damping. Line 48 represents the unsprung mass transmissibility for normal stiffness and large damping. Likewise, line 50 represents the unsprung mass transmissibility for small stiffness and small damping. The unsprung mass transmissibility can also be divided into the five above mentioned frequency ranges. From the figures, it is clear that the transmissibility shape in different frequency ranges can be changed dramatically by varying stiffness and damping.

[0029] Table 1 lists the preferred control strategies for specific frequency ranges. The soft stiffness is not included beyond the body mode frequency range even though very effective, as shown in Figure 3. The soft stiffness is not included because the stiffness control consumes a large amount of power in those frequency ranges. Therefore, the stiffness control is applied up to 3 – 5 Hz, which is referred to as a low-bandwidth active suspension control

Control Strategy vs. Domain for T-Shaping Control

	Frequency Range	Adopted Control Strategy
Ride Control (i.e., Ride Comfort)	Low	Passive Suspension (i.e., DDPM idle) or Stiff Suspension Strategy
	Body Mode	Small Stiffness (and Skyhook)
	Medium	Low Damping (and Skyhook)
	Wheel-hop	High Damping or Groundhook
	High	Low Damping
Roll Control (i.e., Handling Control)	Large Stiffness with High Damping (i.e., Stiff Suspension Strategy)	
Pitch Control (i.e., Dive/Squat Control)	Large Stiffness with High Damping (i.e., Stiff Suspension Strategy)	

Table 1

[0030] The control strategies of Table 1 are defined below:

Passive Suspension refers to the suspension when DDPM is idle in the context of this embodiment.

Soft Stiffness Control is the negative feedback of the measured relative displacement.

Large Stiffness Control is the positive feedback of the measured relative displacement.

Low Damping is the negative feedback of the relative velocity, which is either measured or estimated from the measured relative displacement.

High Damping is the positive feedback of the relative velocity, which is either measured or estimated from the measured relative displacement.

Ground Hook is the feedback based on the linear velocity of the unsprung mass.

Sky Hook is the feedback based on the bounce, pitch and roll velocity of the sprung mass.

Large stiffness with High damping also referred to as 'stiff suspension strategy', combines both large stiffness control and high damping.

[0031] The combination of control strategies for ride control is further described in United States Patent Application No. 10/422,603, filed April 23, 2003, which is incorporated herein by reference. A low damping strategy should be sufficient for ride control if the compressible fluid strut has CVSA valves except in body mode and wheel-hop mode frequency ranges. Otherwise as a low bandwidth suspension system without CVSA the suspension should be passive except in the body mode frequency range. Fundamentally, a suspension using a compressible fluid strut with CVSA valves is considered a broad bandwidth active suspension system. Alternatively, a suspension system compressible fluid strut without CVSA valves is considered a low bandwidth active suspension system. The ride control for a broad bandwidth active suspension control can be expressed as equation (1):

$$\begin{aligned}
 RideControl = & \frac{A_1}{\varepsilon + \sum_{i=1}^5 Ai} \times PassiveSuspension \\
 & + \frac{A_2}{\varepsilon + \sum_{i=1}^5 Ai} \times Soft_StiffnessControl + \frac{A_2}{\varepsilon + \sum_{i=1}^5 Ai} \times SkyhookControl \\
 & + \frac{A_3}{\varepsilon + \sum_{i=1}^5 Ai} \times LowDamping \\
 & + \frac{A_4}{\varepsilon + \sum_{i=1}^5 Ai} \times (HighDamping \text{ or } Groundhook) \\
 & + \frac{A_5}{\varepsilon + \sum_{i=1}^5 Ai} \times LowDamping
 \end{aligned} \tag{1}$$

where A_i are estimated amplitudes of the pitch acceleration for the corresponding frequency ranges, wherein A_1 corresponds to low frequency range, A_2 corresponds to the body mode frequency range, A_3 corresponds to the medium frequency range, A_4 corresponds to the wheel hop frequency range, and A_5 corresponds to the high frequency range, and ε is a small number selected to avoid singularity.

[0032] The broad bandwidth active suspension control can also be implemented using fuzzy logic. For low bandwidth active suspension, only the first three frequency ranges are considered shown below as equation (2).

$$\begin{aligned}
 RideControl = & \frac{A_1}{\varepsilon + \sum_{i=1}^3 Ai} \times PassiveSuspension \\
 & + \frac{A_2}{\varepsilon + \sum_{i=1}^3 Ai} \times Soft_StiffnessControl + \frac{A_2}{\varepsilon + \sum_{i=1}^3 Ai} \times SkyhookControl \\
 & + \frac{A_3}{\varepsilon + \sum_{i=1}^3 Ai} \times LowDamping
 \end{aligned} \tag{2}$$

[0033] Figure 5 shows an embodiment of the control structure for the T-shaping control in accordance with an embodiment of the present invention. Three body accelerations 54 are provided to block 56 which identifies a preferred control strategy based on the frequency range. The three body accelerations 54 need to be converted to bounce, pitch, and roll accelerations. Eq. (1) is applied using the bounce, pitch, and roll accelerations to produce a bounce ride control, a pitch ride control, and a roll ride control, respectively. Then the total ride control 57 can be derived according to the relationship shown below as equation (3).

$$\begin{aligned} TotalRideControl = & \alpha_1 \times BounceRideControl \\ & + \alpha_2 \times PitchRideControl \\ & + \alpha_3 \times RollRideControl \end{aligned} \quad (3)$$

where α_i ($i= 1$ to 3) based on the frequency of vibration and the summation of α_i is equal to 1. The present invention further contemplates that the three body accelerations can be replaced with one body acceleration and two angular accelerations measured by gyros or rate sensors.

[0034] In another aspect of the invention, controller also uses additional sensing information 55 such as steering wheel angle, lateral acceleration, yaw rate, longitudinal velocity, brake pedal and gas pedal to determine which control strategy to employ, as shown in Figure 5.

[0035] The total ride control 57 is then provided to block 58 where the required mean pressure 60 is calculated based on the selected control strategy. Alternatively, the driver of the vehicle may also manually select the control strategy through a manual selection signal 52. Similar to the ride control strategy, other formulations can be used to combine ride control, handling control and dive/squat

control by applying techniques such as fuzzy logic or a weighting approach. The combination of the ride, handling, and dive/squat control strategies to produce the required mean pressure 60 in the compressible fluid struts 64 can be described by the following relationship:

$$\begin{aligned} \text{RequiredMeanPressure} = & \beta_1 \times \text{TotalRideControl} \\ & + \beta_2 \times \text{HandlingControl} \\ & + \beta_3 \times \text{DiveSquatControl} \end{aligned} \quad (4)$$

[0036] Where β_i ($i = 1$ to 3) is the coefficients decided by the vehicle status, and summation of β_i is 1. The required mean pressure for each strut will be calculated relative to the suspension travel and vehicle velocity. The required mean pressure signal 60 then is sent to the DDPM controller 62, which can control pumping, motoring, or idling for each cylinder corresponding to each of the compressible fluid struts 64. This closed-loop control dynamically adjusts the suspension transmissibility for desired performance.

[0037] Figure 6 shows the sprung mass accelerations by exposing the vehicle to pure-tone vibrations. Line 70 represents the sprung mass accelerations due to pure tone vibration on a passive suspension. Alternatively, line 72 represents the sprung mass accelerations on an active suspension controlled according to the present invention. Figure 7 shows the sprung mass acceleration resulting from discrete events. Reference numeral 78 indicates a step up event while reference numeral 80 indicates a step down event. The sprung mass accelerations for a passive system are represented by line 74 while the sprung mass accelerations for an active system are represented by line 76. In Figures 6 and 7, the comparison between active and passive suspensions clearly shows that the active suspension

with T-shaping control can significantly improve the primary ride. Figures 8a and 8b represent the results of a handling simulation illustrating the roll dynamics while the vehicle performs a constant radius maneuver. The lateral acceleration of the vehicle during the constant radius maneuver is represented by line 90. Line 94 represents the vehicle roll angle of an active suspension system controlled according to the present invention corresponding to the lateral acceleration during the constant radius maneuver. Alternatively, line 92 represents the roll angle of passive suspension system corresponding to the same lateral acceleration. Figure 8b shows that the roll angle can be reduced by almost half with the active suspension control strategies of the present invention, while the vehicle has a lateral acceleration of 1g. Furthermore, the amount of oscillation is also reduced with the active suspension.

[0038] While the T-shaping control described above is for active vehicle suspensions implementing compressible fluid struts, this control strategy can be applied to other active suspensions. Since the T-shaping control is based on tuning stiffness and damping, the suspension transmissibility can be properly altered for the desired dynamic performance including soft, stiff or in-between suspensions.

[0039] More importantly because damping coefficient and stiffness of each damper are explicitly tuned, their ranges can be properly determined based on the hardware conditions so that negative values can be avoided. Thus, the T-shaping control can avoid system destabilization for active suspension, while exploiting the maximum hardware capability.

[0040] As a person skilled in the art will readily appreciate, the above description is meant as an illustration of implementation of the principles this invention. This description is not intended to limit the scope or application of this

invention in that the invention is susceptible to modification, variation and change, without departing from spirit of this invention, as defined in the following claims.